# THE EFFECT OF LOW FREQUENCY RADIO WAVES ON BIOLOGICAL MATERIALS

Final Report

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OBJECTIVES: To investigate the effects of low frequency radio waves on viable seeds of <u>Zea maize</u>, as a function of frequency, intensity and exposure length.

SUMMARY OF RESULTS:

Two separate experimental approaches were followed. The first consisted of irradiation of dry seeds at various frequencies, varying field strengths, with various times of exposure, moisture content and temperature. Statistical investigation of changes in germination percentages of these treated seeds was made and compared with suitable controls.

The second experimental approach was measurement of dielectric constant, dissipation factor, and equivalent parallel resistance of the grain, with varying conditions of temperature and moisture content.

Study of germination percentages for various treatments seldom reveals more than one-half percent difference between the controls and test samples. One case showed a 1.1% difference, which is statistically insignificant.

Fields of 60,000 volts per centimeter produced heating effects which raised the temperature 20°C, but for the conditions for the other experimental work, temperature rises of only 1° to 2°C were noted. This temperature rise, and a possible statistical indication of an overall trend toward lower germination percentage for the entire group of test samples, were the only effects demonstrated by irradiation.

The search for molecular absorption in seeds showed only two frequencies producing a reliable indication. Graphs of resistance vs. frequency with changing moisture content, show distinct absorption at 300 kilocycles per second for moisture contents above 20% by weight. This absorption frequency corresponds to that expected for ice, when extrapolated to room temperature. Another absorption maximum was found at one megacycle per second, at -180°C, apparently due to a molecule whose room temperature absorption frequency occurs higher than those frequencies used in this work.

Graphs of equivalent parallel resistance at various frequencies as a function of temperature are linear on a semi-logarithmic plot. These are typical of ionic conduction whose activation energy is calculated as 0.2 electron volts, under the experimental conditions.

Calculations based on room temperature data regarding the DC capacitance, paralled conductance, and space charge capacitance indicate about $5 \times 10^{11}$ charge carriers per cubic centimeter of seed material, having a mobility of $1.2 \times 10^{-9}$ $cm^2$/volt-second. The agreement of experimentally determined curves of these quantities, with those predicted by theory, indicate these calculations to be of the correct order of magnitude.

DETAILED RESULTS:

The detailed results and conclusions of the work done on this contract have been prepared in thesis form, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, by Mr. Philip Cholet. The material is included here in supplement form.

SUPPLEMENT

# INVESTIGATIONS ON THE FREQUENCY DEPENDENT ELECTRICAL PROPERTIES OF BIOLOGICAL MATERIALS

## I. Introduction

### A. Background and Purpose

For at least 30 years various workers have been concerned with the effects of electromagnetic fields on biological systems. However, there has been slight agreement as to whether the observed results have been due to effects of heating in these fields or to some specific effect demonstrable only at certain frequencies.

This investigation was undertaken for the purpose of searching for some such specific effect in the frequency region from 100 cycles per second to 50 megacycles per second.

### B. Previous Work

(1) Animal

Exposure of animals to electromagnetic fields was apparently begun by Schereschewsky[1], who exposed mice to various frequencies. The mice were irradiated in the fields produced between large condenser plates. Using frequencies between 18 and 66 megacycles, he was able to produce necrotic areas and hemorrhaging, and if the exposures were prolonged, death of the animal was common. This work was continued using transplantable tumors on mice. Schereschewsky noticed that after exposing these tumors to a field, they become smaller and softer. Out of four hundred and three mice, treated, one hundred recovered tumor-free, while no recoveries occurred in two hundred and thirty untreated control mice.[2]

1. Schereschewsky, J.W., U.S. Pub. Health Reports XLI (1926) 1939-63
2. Schereschewsky, J.W., U.S. Publ. Health Reports XLIII (1928) 927

Headlee and Burdette[3] investigated a possible selective action of a high frequency field on nervous tissue. They reported differences in the lethal exposure time for insects with varying amounts of nervous tissue.

A rather interesting experiment along this same line was performed by McKinley[4], who treated chicken embryos with a field in such a fashion that the heat produced was the same as that required for incubation. When irradiation was delayed until after the embryo had developed more than 48 hours, a lethal result was observed in 76% of the cases. But when irradiated in the first 48 hours of development, before the differentiation of the nervous tissue, the embryo showed no apparent effects.

(2) Plant

Gosset, in 1924 was the first to apply the vacuum tube oscillator to the irradiation of plant materials.[5] He reported that exposure of plant tumors in <u>Geranium</u> resulted in eventual necrosis of the tumors.

McKinley[6] worked on corn seeds, observing that exposures of 5 minutes to 1 hour were highly lethal to seeds of Golden Bantam, although the internal heat developed was considerable. Exposures of 30 to 40 seconds produced negligible heating and growth after germination was slightly accelerated.

3. Headlee, T. and Burdette, R. <u>Jour. New York Ento. Soc.</u> XXXVII (1929) 59
4. McKinley, G.M. <u>Proc. Penn. Acad. Sci.</u> IV (1930) 43-46
5. Gosset, A. and others, <u>Compt. Rend. Soc. Biol.</u> XCI (1924) 626-628
6. McKinley, G.M. <u>op. cit.</u> IV, 43-46.

In more recent years the experimental information has become a bit more complete. Nyrop[7] reported killing of bacteria and inactivation of virus at very moderate temperatures using frequencies of 20 megacycles. However, Miyamoto[8] reports no effects on potato viruses using frequencies of 10 mc, 33 mc, 830 mc, and 3000 mc.

Lion and Gould[9] irradiated dried yeast at 25 megacycles and 200 volts/cm. They report that 55% were killed in 15 minutes, but a 30 to 40% increase in the growth rate was noted for short exposure. This increase in growth rate was also found in Penicillium cultures, and resulted in a 200 to 300% increase in the production of penicillin.

Landi[10] exposed conidial suspensions of Aspergillus to a radar beam of unspecified frequency and obtained exponential survival curves. On the other hand, MacDonald[11] exposed mycelia to 3000 mc radar pulses for up to one hour and found no effects other than drying by the increased temperature.

To return to the recent work on plants, Lambert[12] and others report on several seed species. Voltages of 1500 to 2900/cm were used for periods up to 5 minutes. They observed lethal effects and reduction of germination percentages.

7. Nyrop, J. Nature CLVII (1946) 51
8. Miyamoto, Y. and Indo, H. Ann. Phytopath Soc. Japan XVI (1951) 127 - 130.
9. Lion, K.S. and Gould, B.S. Amer. Brewer LXXXII (1949) 21-24
10. Landi, R. Nuovo Giorn. Bot. Ital. LVI (1949) 339-344.
11. MacDonald, J.A. Ann. Appl. Biol. XXXIV (1947) 430-434.
12. Lambert, D.W. and others, Agron. Jour. XLII (1950) 304-306.

Jonas[13,14] exposed dry seeds of carrots, onions and celery at 44.5 megacycles in fields of 350 volts/ cm. He observed an increase in germination percentage as time of exposure increased, followed by a decrease in germination at longer exposure times. Analysis of his exposed seeds showed that the total sugars had been halved.

Seeds of Vicia were exposed to 107 mc fields by Bellinzaghi,[15] who reports results similar to those of Jonas; germination may be either improved or inhibited depending on the length of the exposure.

Cholet[16] worked on dry corn seeds at frequencies from 5000 cycles per second to 200,000 cycles per second with fields of 600 volts/cm. The effect reported was a definite increase in lethal effects at lowest frequencies, with exposure times of 1 hour.

It is, therefore, apparent that while there is general agreement that fields may produce effects on living materials, no such agreement may be found as to the actual nature and specificity of these effects.

## II. Irradiation Experiments

### A. Theory

While any recent text on Cytology, such as Sharp[17] may be consulted for detail on cellular structure, it may be useful to remark on certain aspects of structure which have significance

13. Jonas, H. Electronics XXVI (1950) 161.
14. Jonas, H. Physiology Plantarum V (1952) 41.
15. Bellinzaghi, Ff. Atti. Soc. Ital. Sci. Nat. LXXX (1941) 226-243
16. Cholet, P. "An Effect of Molecular Rotation on Living Material", Unpublished Master's Thesis, Department of Physics, Syracuse University, 1948.
17. Sharp, L.W. Fundamentals of Cytology 1st. ed. McGraw-Hill, New York, 1943.

for this problem. The cell may be considered as a conducting sphere surrounded by a thin insulating layer. For most of the common biological materials the dimensions of the cells may be in the region of a few microns, and in the case of multi-cellular organisms or tissues, these small cells are in contact or nearly so.

Inside the cell membrane, and cell wall if present, there is a complex structure with various subdivisions, but the major feature of the structure is its colloidal and gel form. In living materials water forms the preponderance of the structure, with ions of various salts present in closely controlled amounts. Rigidity is given to the material by the formation of an organic gel, largely protein in nature, which of course may include other materials such as oils and carbohydrates in colloidal suspension.

As may be surmised, this type of structure predicts to a reasonable extent the electrical characteristics of cells and tissues. A suspension of cells, or a moist tissue would be expected to conduct electricity through the intercellular fluids at low frequency or at DC, but as the frequency increased, capacitative effects would become more important, until at very high frequency, the susceptance component would greatly predominate over the conductance component. Cole[18] and others have been concerned with this problem and worked out various relationships between cell concentration and impedance.

18. Cole, K.S. "Electrical Conductance of Biological Systems" Cold Springs Harbor Symposia on Quantitative Biology Vol. 1 Darwin Press, New Bedford, 1933.

When, however, the single cell is considered, the impedance changes as a function of frequency become a bit more complex, due to the ionic conduction component within the cell. This will be treated more completely in a subsequent section.

Thus if a cell or group of cells is placed in the field between condenser plates, and the field varies as a function of time, it is possible to predict with fair accuracy the electrical behavior by ordinary circuit theory. However, since the structure of the cell includes large polar molecules, it is necessary to have a knowledge of the behavior of these molecules as a function of frequency to predict the electrical behavior completely.

Since this work is to be conducted at lower frequencies, it is worthwhile to examine the possibility of molecular rotation, and disregard vibrational modes. In general, for molecules, the vibration frequencies are a factor of 10 to $10^3$ higher than the rotational frequencies. In large molecules, the factor would be even greater, since the rotation frequency decreases inversely as the mass, while the vibration frequency decreases as the square root of the mass.

Fundamental considerations of permanent dipoles lead to the result that in free rotation the frequency is given by[19] $f = 2BJ$ where J is the rotational quantum number and B is a constant determined from the dimensions and mass of the molecule. For purposes of illustration, the rotational frequencies expected of zein, a common corn protein, may be calculated. The length

19. Hertzberg, G. Molecular Spectra and Molecular Structure. I. Spectra of Diatomic Molecules 2nd ed. D. VanNostrand, New York, 1950 p. 73

of the molecule is 320 Angstroms, with an average thickness of 8 Angstroms. This may be either a rod shaped or ellipsoidal molecule[20] with a molecular weight of 40,000, corresponding to a mass of $6.4 \times 10^{-20}$ grams. The moment of inertia for the rod shaped form is $5 \times 10^{-32}$ gm.cm.$^2$ If J were equal to 1, this would yield a frequency of 3000 cycles per second. However, calculations of the rotational quantum number for this molecule at room temperature gives a J of $6 \times 10^4$, so that the most probably frequency observed would be $1.8 \times 10^9$ cycles per second.

Aside from this type of resonance rotation there remains the probability of Debye type of relaxation phenomena occurring. This is differentiated from the resonance type of absorption mainly by the absence of restoring forces. When a dipole is oriented by the field under these conditions, it loses its orientation by collision processes, and thus is strongly dependent on temperature. Instead of an oscillation frequency, a Debye type mechanism is characterized by a relaxation time $\tau$ which is a measure of the time taken for the exponential decay of orientation in the absence of the aligning field.

In the case of liquids and solids, such as may be present in the cell, there arises the necessity of making some corrections to the simple theory of isolated rotators. It appears experimentally that resonance rotation is very unlikely[21] and is transformed into a type of resonance oscillation about an equilibrium position.[22] Some variation in this has been observed in

20. Wyman, J. J. Biol. Chem. Soc. XC (1931) 443.
21. Hertzberg, G. op. cit. p. 124.
22. Frohlich, H. Theory of Dielectrics, 1st. ed. Oxford, London, 1950.

materials which seem to provide more than one or two equilibrium positions of lowest energy for the rotator.[23]

There is also a pronounced effect on Debye type absorption when the solid or liquid state is considered. Here, of course, there is a phenomenon similar to viscous damping, with the result that $\tau$ becomes greater with denser media. This effect is described by the relationship:

$$\tau = \frac{4\pi\eta r^3}{kT}$$

which has been experimentally verified by Perrin,[24] Again referring to zein, $\tau$ has a value at 25°C of $24 \times 10^{-8}$ in ethanol. So that assuming the cellular fluids to be equally or more viscous gives relaxation times corresponding to the frequencies used in this work.

A further, and rather important consideration of the effects of the radiation field is that effect of dielectric heating. This depends directly on the rate of energy loss from the electric field, as may be shown in the following treatment adapted from Frohlich.[25]

It is known from elementary physics that the loss of energy per unit volume is described by $L = \sigma E^2$

or in the case of AC by $L = 1/2\,\sigma E_o^2$

where $\sigma$ is conductivity and $E_o$ is related to E by $E = E_o (\cos \omega t)$

23. Hoffman, J.D. J. Chem. Phys. XX (1952) 541 - 549
24. Perrin, F. J. Physique et Rad. V (1934) 487
25. Frohlich, H. op. cit. passim

Now considering the relationships of E, the electric field and D, the displacement, in a periodic field D may have some phase difference $\Phi$ from E, depending on frequency. So that $D = D_o \cos(\omega t - \Phi)$ and from this by trigonometric manipulation

$$D_1 = D_o \cos \Phi$$

$$D_2 = D_9 \sin \Phi$$

This allows the introduction of two dielectric constants in such a fashion that $D_1 = \epsilon_1 E_o$ and $D_2 = \epsilon_2 E^o$

There is the further relation that $\tan \Phi = \frac{\epsilon_2}{\epsilon_1}$

Suppose now that $\sigma$ is written as frequency dependent, in the following form:

$$\sigma(\omega) = \frac{\omega E_2 (\omega)}{4\pi}$$

When this is substituted in the relationship for loss

$$L = \frac{\epsilon_2 E_o^2 \omega}{8\pi}$$

Since most collections of data do not give values for $\epsilon_2$ it may be rewritten as

$$L = \frac{\epsilon_1 E_o^2 \omega}{8\pi} \tan \Phi$$

In practical units this reduces to $W = \frac{\epsilon V^2 f\Phi}{18 \times 10^{'}}$

where $V^2$ is in volts/cm.; f is frequency; $\epsilon$ and $\Phi$ have their usual significance; and W is watts/cm$^3$.

To sum up then, when a biological material is exposed to an electromagnetic radiation field of some frequency, there may be the expectation of producing heat, or orientation of molecules. It may also be assumed that dipolar ions can react in much the same fashion as the polar molecules, and there will be the possibility, too, of a normal ionic or electronic conduction component through the material if it is in contact with conducting electrodes.

The selection of the material for experiment in this work was done with several objectives. The primary need was to obtain a material in which a frequency specific effect might be observed, without interference from heating. A secondary requirement was to use material which could be easily handled statistically. In addition, the material chosen should be readily available and reasonable inexpensive in large quantities.

In order to avoid the large scale production of heat it appears from the calculation of heat loss that dielectric constant, power factor, and applied field should all be low. Since biological systems are mainly water, the first assumption is that dehydrated material should be used, thus reducing the dielectric constant, and incidentally reducing ionic conductivity in the cells and intercellular spaces. This assumption is supported by experimental work done by others.[26] In the event that heat cannot be minimized, a material should be chosen which can tolerate a reasonably high temperature without damage.

26. Dunlap, W. and Makower, B. Jour. Phys. Chem. XLIX (1945) 601

These two considerations indicate the possibility of using seeds as the test material. Ordinary corn, Zea maize, fits the requirements fairly well as to convenience of handling for statistical work, and is easily obtained. In normal field corn the moisture percentage is usually low after drying for storage, running about 8% to 11%.[27] It also has a very good tolerance for elevated temperature. Siegel[28] has also found that continued temperatures greater than 40°C are necessary to produce an appreciable change in germination percentage.

Using measured values of $\epsilon_1$ and $\Phi$, a calculation for the heat generated at 100,000 cycles per second indicates a temperature rise of about 5°C per hour in a field of 1000 volts/cm. This is certainly below any figure which might affect the results.

The dormant seed has its metabolic processes proceeding at a very slow rate. If it were possible to affect metabolism in some way by the application of the field, it seem reasonable to assume that the effects observed would be either an increase in metabolic rate, giving more rapid germination, or a decrease, which under these conditions would probably mean death. Therefore, it was decided to use decrease in germination percentage as an indicator of any lethal effect. This being an all or none type of phenomenon, it lends itself to easier statistical investigation, and is more readily measured than changes in growth rates after germination, or other similar measurements.

27. Miller, E.G. Plant Physiology, 2nd ed. McGraw-Hill New York, 1938.
28. Siegel, S.M. Bot. Gaz. CXII (1950) 57

On the basis of the previous discussion of possible electrical effects, it would seem that any lethal effect would be due to an interference with metabolism caused by reorienting some of the large polar molecules or ions present in the cells.

B. Experimental Work

Most of the work reported in the literature has been done by exposing the materials to the field between condenser plates. This has certain advantages, in that the configuration of the field is accurately known and the plates may be made to support the materials during exposure. In the present work, it was thought worthwhile to rest the material on the lower plate and have the upper plate positioned in such a manner that the seeds did not quite touch it. This eliminated any effects from conduction currents.

Apparatus used to apply the AC potentials to the condenser plates was for the most part conventional in form. A high voltage amplifier was constructed which covered the frequency range from 500 cycles to 200,000 cycles per second, with a voltage on the condenser plates up to 1500 volts/cm. To go to higher frequencies a Tesla coil was constructed capable of supplying 30 to 40 kilovolts at the plates, and at still higher frequencies up into the megacycle region a push-pull oscillator was used, capable of 3000 volts output on the condenser plates up to 30 megacycles.

For certain purposes an automobile spark coil was used, which gave voltages of 35,000, and a Kelly-Koett X-Ray transformer was used for very high voltage work at 60 cycles per second. All voltages are RMS.

The procedure followed in all the irradiation was as follows: With frequency and voltage selected, 50 seeds were placed in the condenser and irradiated for the length of time specified for that run. Temperature checks were run with a thermocouple imbedded in an extra seed placed in the field. After exposure to the field, the seeds were rolled up in a clean hand towel, which was soaked in water and squeezed free of its excess moisture. This " rag doll" was then placed in an incubator and kept at 35°C for three days. At the end of this time, a germination count was made. The sole criterion of germination was the appearance of the root or stem shoot through the seed coat.

In order to secure accurate control measurements, for each group of 50 seeds exposed to radiation, another group of 50 was tested for germination by the rag doll method described above.

The original plan of procedure contemplated a general survey of frequency effect, starting at 500 cps and going on into the megacycle region. It is rather futile to attempt a definite statement of what frequencies to use, since the polar molecules and ions in the cells may be in varying states of combination, and there is a large variety of molecular species present. Also, there is no available information on the viscosity of cellular material in the dried state which would lead to a prediction of relaxation time. On the basis of the work done by previous workers it was felt that an exposure of one or two hours in a field of 1000 volts/cm. should be sufficient to produce some change in germination percentage.

Exposures were begun at 500 cps for 2 hours. Next 1000 cps was tried, then 2500 cps, followed by 5000 cps and 100,000 cps. All were done for 2 hours at 1200 volts/cm. at room temperature. Each of these runs was duplicated 5 times. Results of this work are tabulated in Table I.

When there was sufficient information to indicate that no effects were being produced, some of the work was repeated with 7 hour exposures. 500 cycles, 2500 cps and 5000 cps were repeated in this manner, as shown in Table II. No apparent positive results occurred with this treatment.

It was then decided to increase both the field frequency and intensity. A set of runs was made, of 7 hours duration, at frequencies of 125 kc, 145 kc, and 220 kc, all at room temperature and with a 12,000 volts/cm field. Table III shows the results of this work.

A brute force approach was next attempted, in the sense of going to very high field strength. By the use of a transformer giving 240 kilovolts peak, it was possible to expose the seeds to a field of 60 kilovolts per centimeter, peak, when placed in transformer oil between polyethylene insulating sheets. Although the field frequency was only 60 cps, there was a temperature rise in these seeds of 22°C in 2 hours. It is interesting to note here that under these conditions, the predicted temperature rise is approximately 35°C per hour. Germination tests with these seeds were unsuccessful, since the transformer oil has a lethal effect on both the controls and test seeds. No other liquid dielectric was found available which would withstand the very high fields without also being lethal to the seeds,

An extension of the brute force method was attempted using the damped weve train obtained from an automobile spark coil. When the discharge of one of these coils is examined on the oscilloscope it may be seen that the shape is sinusoidal, rapidly damped, and consisting of a fundamental frequency of approximately 150 kc. Heavy duty coils of this type may develop up to 35,000 volts. Groups of seeds were exposed to fields of 20,000 volts/cm at room temperature for periods of 6 hours, with results as shown in Table IV.

On the premise that perhaps the effects would be moisture sensitive, one set of tests was run on thoroughly dehydrated seeds. These were pumped in a vacuum of 5 microns at room temperature for a month, and then exposed at 5000 cps for 7 hours in a field of 1200 volts/cm. Again it was apparent that there was no effect. The opposite approach was tried, repeating this experiment with seeds which had been soaked in water for 4 hours, but again with negative results.

The final variable tested was temperature. By raising the seeds to 48°C they are already in a region where lethal results may be expected[29] and any lethal effects of the field might be more readily observed. One set of tests was run at 125 kc and 12 kilovolts/cm for 5 hours. The other set was done at 500 cps and 1200 volts/cm for 5 hours. This last set was repeated 15 times and investigated statistically by small sample methods. This gave a value of "t" of .77, corresponding to a probability of .5. Stated differently, this means that for this number of

29. Siegel, S.M. op. cit.

tests, there is only one chance in two that the difference between average germination of the samples and tests is not due to chance alone.[30] This is generally accepted to be statistically insignificant.

As a final experiment it was decided to run another sample set of seeds exposed to 5000 cps. These were done for 2 hours and 1200 volts/cm and at room temperature. The results are shown in Table VII. This group was also run through a statistical test, with the result that the probability of variation between samples and tests is only .6, again a non-significant value.

It thus appeared that no genuine effect could be demonstrated at the frequencies and fields chosen. However, a very interesting result appears in the evaluation of the overall group of tests done at all frequencies and under all of the mentioned conditions. This results in the parameter "t" being 1.75, corresponding to a probability of just under .1, which is on the borderline of statistical significance. To state the meaning differently, there is less than one chance in ten that the average germination of the tests is different from the average germination of the controls due to probability alone.

30. Villars, D.S. Statistical Design and Analysis of Experiments 1st ed. W.C. Brown, Dubuque, 1951 passim.

## III. Measurements of Constants

### A. Theory

The amount of time necessary for irradiation experiments, coupled with the lack of any definite evidence for results, indicated that some sort of survey over a wide frequency range should be conducted, using some measurement other than change in germination percentage. A reasonable approach to this is found by considering the relationship of the polar compounds in the cell to measureable constants such as the dielectric constant and dissipation factor.

The interrelationship between dipole moment, temperature, and frequency is rather involved, especially for solid materials, so that perhaps the greatest clarity may be obtained by developing first the relation between polar molecules and the static dielectric constant of a gas.

When dealing with more than one dipole, there is normally an interaction, but as an approximation it may be assumed that the interaction energy $\mu^2 N_o$ is less than kT, where $N_o$ is the number of dipoles per unit volume. It is also taken from elementary theory that $\epsilon_s - 1 = \frac{4\pi N_o m}{E}$

in which $\bar{m}$ is the vector sum of the moments of all N molecules. Since $-E\mu\cos\theta$ is the energy of the dipole in the applied field and if the behavior of the dipole be considered statistically, it is possible to write

$$e^{E\mu\cos\theta/kT}\sin\theta d\theta \Big/ \int_0^\pi e^{E\cos\theta/kt}\sin\theta d\theta$$

This equation gives the probability of finding $\mu$ in a direction forming an angle between $\theta$ and $\theta + d\theta$ with E.

Now by assuming that the field is weak enough so that $\frac{\mu E}{kT} \ll 1$, $\cos\theta$ may be averaged to be:

$$\overline{\cos\theta} = \int_0^\pi \cos\theta e^{E\mu\cos\theta/kT} \sin\theta d\theta \Big/ \int_0^\pi e^{E\mu\cos\theta/kt} \sin\theta d\Phi = \frac{\mu E}{3kT}$$

Thus by a short manipulation

$$\epsilon_S - 1 = \frac{4\pi\mu^2 N_o}{3kT} + 4\pi\alpha_o N_o$$

which clearly shows that the static dielectric constant depends both on temperature and dipole moment.

By a series of assumptions, Onsager[31] has improved on this statement of the static constant in the case of a pure dipolar liquid, with the result

$$\epsilon_s - n^2 = \frac{3\,\epsilon_s}{2\,\epsilon_s + n^2} \; \frac{4\pi\;{}^2 N_o}{3kT} \left(\frac{n^2 + 2}{3}\right)^2$$

where n is the refractive index of the liquid. For various reasons[32] the Onsager approximation is preferred for most work with liquids and even solids, so that it may be seen that temperature and the polar nature of the molecules will still affect the measured dielectric constants.

31. Onsager, L. J. Amer. Chem. Soc. LVIII (1936) 1486.
32. Frohlich, H. op. cit. p. 53.

It now remains to be seen how the measurement of dielectric constant as a function of frequency can offer information. Debye[33] has performed all the basic work on this subject, but certain results are important here.

In a previous section ( page 7) mention was made of the relaxation time $\tau$ as the measure of time taken for the exponential decay of orientation of molecules after the aligning field is removed. A function may be written to describe this decay, as by $\alpha(t) \propto e^{-t/\tau}$

Recalling the remarks made about the relationships of D and E, it turns out that this relationship could be written

$$D(t) = \epsilon_\infty E(t) + \int_{-\infty}^{t} E(u)\alpha(t-u)\,du$$

By differentiating this, with further manipulation it is possible to obtain

$$\tau \frac{dD(t)}{dt} = \epsilon_\infty \tau \frac{dE(t)}{dt} + \tau\alpha(0)E(t) - \int_{-\infty}^{t} E(u)\alpha(t-u)\,du$$

Adding these two equations results in

$$\tau\frac{d}{dt}(D - \epsilon_\infty E) + (D - \epsilon_\infty E) = (\epsilon_S - \epsilon_\infty)E$$

where the constant $\alpha(0)$ has already been evaluated.

Returning to the consideration of D and E, it is possible to

write $\epsilon = \epsilon_1 + i\epsilon_2$ making it possible to

write $E = E_0 e^{-i\omega t}$.

$D = \epsilon E$ remains valid so that $\frac{dE}{dt} = -i\omega E$, $D = \epsilon(\omega)E$,

$$\frac{dD}{dt} = -i\omega\epsilon(\omega)E$$

33. Debye, P. Polar Molecules 1st ed. Dover, N. Y. , 1929

Putting these into the differential equation shown above gives

$$\epsilon(\omega) - \epsilon_\infty = \frac{\epsilon_s - \epsilon_\infty}{1 - i\omega\tau}$$

Now separating the real and imaginary terms lead to

$$\epsilon_1(\omega) - \epsilon_\infty = \frac{\epsilon_s - \epsilon_\infty}{1 + \omega^2\tau^2} \quad \text{and} \quad \epsilon_2(\omega) = \frac{(\epsilon_s - \epsilon_\infty)\omega t}{1 + \omega^2\tau^2}$$

and to the expression for loss angle

$$\tan\phi = \frac{\epsilon_2}{\epsilon_1} = \frac{(\epsilon_s - \epsilon_\infty)\omega\tau}{\epsilon_s + \epsilon_\infty\omega^2\tau^2}$$

From a measurement standpoint, this is all the information needed to determine $\tau$. At any frequency $\epsilon_1$ and $\Phi$ may be measured, and if a ballistic method is used, $\epsilon_s$ may be determined. By measuring over a wide enough range of frequencies it should be possible to find a maximum value for $\Phi$. Manipulation gives

$$\frac{\partial \tan\phi}{\partial\omega} \quad \text{and} \quad \omega_\phi = \frac{1}{\tau}\sqrt{\frac{\epsilon_s}{\epsilon_\infty}}$$

and the measurements would be complete for determining $\tau$ and $\epsilon_\infty$

While $\epsilon_\infty$ has small interest, the determination of $\tau$ could be quite useful in furnishing information as to the internal conditions of the cell. Debye[34] gives the relationship

$$\tau = \frac{\zeta}{2kT} = \frac{4\pi\eta a^3}{RT}$$

where a is the radius of the orienting material and $\eta$ is the viscosity of the medium by which it is surrounded. This then could give some knowledge of the size of the polar groups in the cell, and the state of the surrounding materials.

It is obvious, however, that the determination of a single relaxation time will hardly be sufficient to describe intra-cellular conditions. The cell consists of many different molecules,

34. Ibid.

of varying size and polarity, so a distribution of relaxation times would be expected. The approach to this problem is in principle, at least, identical to that just described, and several maxima for Φ would be expected. A graph of dielectric constant as a function of frequency will show immediately whether or not such a distribution of sizes and relaxation time exists. Figure 12, taken from Shack[35] illustrates what may happen in a mixture of two molecules of different size and moment. In the low frequency part of the curve, the orientation effect is sufficiently great to give a high dielectric constant. As the frequency is increased, the molecule can no longer follow the field as well, due to its long relaxation time, and the dielectric constant will decrease. Finally a region is reached in which the molecule is completely unable to follow the field, and the dielectric constant levels off, being due now to the smaller molecule. This in turn goes through the same sequence of events, resulting in the curve shown.

Under certain circumstances, even more information may be obtained from dielectric constant measurements. In the event that the molecules in the cell have some preferential orientation with regard to one another the effect known as hindered rotation may appear. This is not a true spinning of the molecule on its axis, but a reorientation into certain positions which are favorable from the standpoint of their potential energy. Frohlich[36] and others[37] have worked out the theoretical relations between dielectric constant and potential energy wells. This is a rather complex problem and too unwieldy to include here.

35. Shack, J. and others. Ann. New York Acad. Sci. XL (1940) 371
36. Frohlich, H. op. cit. p. 96.
37. Hoffman, J.D. J. Chem. Phys. XX (1952) 541 - 549

The results of their work have the following significance for this problem. If a graph of the dielectric constant at any given frequency as a function of temperature is constructed, the occurrence of a sudden break in the curve at which the constant takes on a new value is an indication that the molecules are "frozen in" at lower temperatures. Meaning simply that they are capable at lower temperature of orienting only into certain positions determined by their binding to their neighbors. Using the relationships developed in the above references, it would be possible to determine the binding energy of polar groups in the cell.

B. Experimental Work

The experimental data was taken with a General Radio Type 716-C capacitance bridge from 100 cycles to 100 kc, and with a Boonton Type 160-A Q-meter from 50 kc to 50 megacycles, thus affording a region of overlap in measurements.

In order to make the measurements, a dielectric constant cell was constructed, which was in the form of two concentric cylinders, with glass insulation supporting the inner cylinder. Guard electrodes were used to avoid unwanted effects, particularly at the higher frequencies. A spiral of glass tubing was wound around the outer cylinder, so that to obtain temperature variations, transformer oil at the correct temperature could be constantly circulated, and temperature equilibrium attained.

When in operation, the space between the concentric cylinders was filled with corn seeds, and oil circulation begun until the desired temperature was reached. Measurement of temperature at several places in the mass of corn served as a method of determining equilibrium. Then measurements of dielectric constant, capacitance, and dissipation factor could be made as the frequency was varied. Figure 1 indicates the general form of variation of dissipation factor and dielectric constant as the frequency of measurement is varied. Figure 2 shows the variation in measured dielectric constant as the temperature is changed.

It is apparent from an examination of these curves that they represent something other than the curves predicted by the Debye theory. The increase in both dissipation and dielectric constant at low frequencies is particularly bothersome, since to expect these curves to level off or have a maximum would require, on the basis of the theory presented, exorbitantly large molecules and relaxation times. In order to see any small variations in the curves which otherwise might not readily be apparent, it was decided to transform the coordinates in such a way that the final graph would be a straight line in the absence of changes in dissipation factor or dielectric constant.

According to standard texts, such as LePage,[38] dissipation factor, which is equivalent to $\Phi$ used earlier, may be written

$D = \frac{G}{B}$ where G is conductance and B susceptance. By rewriting this, and taking the logarithm of both sides, it can

38. LePage, W.R. Analysis of Alternating Current Circuits, 1st edition, McGraw-Hill, New York, 1952, p. 132.

be seen that $\ln R = -\ln(\omega CD)$. So if D and C were to remain constant, a graph of R against frequency on log-log paper would be linear. The data measured by the bridge and Q-meter may be converted rather simply to equivalent parallel resistance, which is shown plotted in figure 3. Here it may be seen that at higher frequencies the curves are rather linear, but there is a noticeable deviation from linearity at low frequencies, which becomes more pronounced as the temperature is increased. However, the curve run at -180°C is reasonably linear with the exception of a dip at about 1 megacycle. The explanation of this dip was not obvious at this point, but will be referred to later.

Measurements of some powdered components of corn were next made, and the results shown in figure 4. Here again there is reasonable linearity at the higher frequencies while at the low frequencies the curvature sets in strongly. However, there is no evidence from these curves that any absorption points have been passed through.

While no determination of $\tau$ could be made from the data over the ranges of frequency and temperature used, there still remains the question of the cause of the large rise in dissipation factor at low frequencies and high temperatures. The curves of figure 2 show a continuous rise in dielectric constant with increasing temperature, so the likelihood of the molecules being in a "frozen in" state is very small. Work by Bayley[39] indicates that this low frequency rise is due to adsorbed water on the molecules. Girard and Abadie[40] differentiate between adsorbed and bound water.

39. Bayley, S.T. Trans. Faraday Soc. XLVII (1951) 509-517
40. Girard, P. and Abadie, P. Trans. Faraday Soc. XLII (A) (1946) 40

claiming that the free, or adsorbed water contributes to increased conductivity at low frequency, while the effect of the bound water is to increase the moment of the polar groups of the molecules.

With this idea in mind, measurements were made to compare dehydrated seeds with frozen seeds. Figure 5 illustrates the results of this test, indicating that seeds in which all moisture was frozen behave in the same fashion as those from which all adsorbed water was removed. Dehydration of seeds is easily performed by vacuum, which will remove water to below the level at which the percentage of moisture may be determined by weight changes.

A companion to this experiment was performed by adding water to the seeds by soaking for various lengths of time, and measuring the water percentage of the soaked seed. Figure 6 shows how the resistance becomes steadily lower with increasing percentage of water in the seed. The low frequency portions of these graphs at high moisture content are not too reliable in absolute magnitude, because with the high dissipation factor the precision of the bridge measurements decreases.

The most interesting aspect of this experiment is the presence of an absorption dip at about 300 kc, which disappears with increasing dryness. The apparent explanation of this may be found in the examination of the relaxation times of ice as a function of temperature. Auty and Cole[41] published curves of the relaxation time of ice in a linear form, permitting ready extrapolation. By

41. Auty, R.P. and Cole, R.H. J. Chem. Phys. XX (1952) 1309-1314

extrapolation to room temperature, $\tau$ becomes $2 \times 10^{-6}$ second, in reasonable good agreement with the observed location of the absorption dip.

This result indicates both that the method used is capable of detecting the relaxations searched for, and that the water entering the seed is at least in part strongly oriented in the manner of ice. Also, it would indicate that the dip shown in the curve for -180°C on figure 3 is probably a relaxation which would normally be observed at a much higher frequency when at room temperature. Unfortunately, the apparatus was incapable of bridging the gap between about -20° and -180°C in any smooth fashion so that a shift of this dip with temperature could not be observed.

At this point it seemed fairly certain that the observed low frequency effects are connected with the moisture content of the seeds. In order to explain quantitatively the shape of the curves at low frequencies, it was decided to investigate the relationship of ionic effects to the measured quantities.

C. Theory

The qualitative results of having mobile ions in a dielectric are rather easy to predict. This is especially true in the case of a dielectric with an insulating boundary layer. Under these conditions when a field is applied to the dielectric, the mobile ions will slowly migrate in a direction determined by their sign, and pile up at the boundary. This results in an increase in the bound charge on the condenser plates furnishing the field, and from elementary theory is seen to be equivalent to an increase

in the dielectric constant of the material. However, in the case of present interest, that of AC fields, the statement of conditions in the dielectric becomes more complex.

Here it is necessary to know something of the mobility of the ions, defined in cm/sec/volt/cm, and the manner in which ions travel through materials. While there are several alternative modes by which an ion may traverse a crystal lattice,[42] in the case of an amorphous material such as exists within the cell, the physical picture is roughly that of a sphere shouldering its way through a swarm of neighboring particles. This leads directly to a consideration of viscosity, and since it is known that the viscosity of a material varies as $\exp(-E/kT)$, the Arrhenius function of the physical chemist, the conductivity of ionic material should be strongly temperature dependent. In fact it should be possible to determine the activation energy of ionic conduction for the material in the corn seeds by a study of the relationship of resistance to temperature.

A consequence of this viscous drag on ions is that in an AC field it is possible to observe power losses at some frequencies which are quite different from those at other frequencies. In particular, at low frequencies, when the ions can move in phase with the field, the losses should be large, but as the frequency increases, or as the material becomes colder, the ions go out of phase with the field and a more perfect condenser is approached. This, in fact, is what is observed in the measurements on seeds.

42. Seitz, F. "Fundamental Aspects of Diffusion in Solids", Phase Transformation in Solids, Wiley, New York, 1951

The very interesting question arises as to what ions are responsible for the observed effects, and what is their concentration and mobility. Until recently there was no entirely satisfactory approach to determining quantitative facts about these ions or charge carriers. A paper by Macdonald[43] recently appeared, which offers a good method for determining these constants, and the points affecting the work on seeds shall be outlined below.

The theory developed is specifically restricted to the AC behavior of material containing charge carriers of either sign which are mobile in the material but are unable to leave through the electrodes. Under these conditions the admittance of the materials may be written:

$$Y_p = \frac{e(\mu+\mu')c_0}{L} + \frac{ec_0\mu'}{L}\left[\frac{\chi_A\left(1-\frac{1}{\sigma\gamma^+}\right)\sinh\eta^+ - \left(1-\frac{1}{\sigma\gamma^-}\right)\sinh\eta^-}{\chi_A\left(1-\frac{1}{\gamma^+}\right)\left(\frac{L\rho^+}{\sqrt{2M}}\right)^{-2}\left(\eta^+\cosh\eta^+-\sinh\eta^+\right)-\chi_A\eta^+\cosh\eta^+ - \left(1-\frac{1}{\gamma^+}\right)\left(\frac{L\rho^-}{\sqrt{2M}}\right)^{-2}\left(\eta^-\cosh\eta^--\sinh\eta^- -\cosh\eta^-\right.}\right]$$

$$= G_p + i\omega C_p$$

$C_g$ is the normal capacitance of the layer between the electrodes, and $C_p$ and $G_p$ are the terms representing the space charge parallel capacitance and conductance, respectively. The complex Greek alphabet symbolism contains information on the dissociation and recombination rates, the dependence of concentration of negative and positive carriers on their distance from the electrodes, the total concentration of carriers, and finally the mobility and diffusion constants. This is far too complex for easy handling, but the author makes certain simplifying assumptions which may

43. Macdonald, J.R. Phys. Rev. XCII (1953) 4-17.

be applied to the problem. If it is assumed that charge carriers of only one sign are mobile, that there is small dissociation, and that the recombination time of the ions is quite large, it is possible to write the following relations:

$$\nu_r = \omega/k_2 c_o$$

where $k_2$ is the recombination constant and $c_o$ is the carrier concentration.

$$\nu^+ = \frac{\alpha C_g}{G_\infty}$$

where $G_\infty$ is the high frequency limiting value of $G_p$. And from these two $\xi = \dfrac{\nu_r}{\nu^+}$

A further important value is written $G = \dfrac{e\mu' c_o}{L}$ in which L is the distance between electrodes and $\mu'$ is the carrier mobility. "e" has its usual value of charge. By making the proper measurements, $C_o$ the DC capacitance may be obtained, and by writing

$C_o = (r-1)Cg$, r may be determined.

$r = \eta^- \coth \eta^-$ relates r to $\eta$- which in turn is equal to the parameter M in the case at hand. By manipulation of other relations

$$C_o = \frac{\epsilon k T M^2}{2\pi e^2 L^2}$$

may be obtained.

Now there is a complete set of relations from which to find $c_o$, $\mu'$ and $k_2$. It is necessary only to measure DC capacitance, $C_g$ at a very high frequency, $G_\infty$ and the distance between electrodes to obtain $c_o$ and $\mu$. To get $k_2$, however, it is necessary to work back through $\xi$. This may be done by plotting $Cp/C_o$ and

$G_p/G$ against $\sqrt{\nu_m}$ where $\nu_m = \omega \tau_m$ and $\tau_m = \frac{C_o}{G_\infty}$

$\tau_m$ is simply the time constant of $C_o$ in series with $G_\infty$ which means physically the relaxation time associated with the layers at the electrodes. Figure 7 is an example of this type of plot drawn for two values of the parameter M. The author shows that for cases in which all approximation are valid, the two curves will cross at $\nu_m = 1$. In order to find $\xi$ it is necessary to resort to curve fitting. Unfortunately, this is impractical without a computer, since it is already apparent how complex the dependence of $\xi$ on the capacitance and conductance ratios may be.

D. Experimental Work

For this phase of the work it was only necessary to extend the upper limit of the measurements of dielectric constant and dissipation factor. One additional set of measurements had to be made, using the ballistic galvanometer to determine the DC capacitance of the samples. The quantity $C_g$ is known from the high frequency dielectric constant of the cell and its geometry. The required value of $C_p$ is equivalent to the measured value of capacitance at each frequency after subtraction of $C_g$. The conductance $G_p$ is the actual measured value, converted from $R_p$ used in the previous measurements. In order to determine $G_\infty$ it is necessary to extend the upper frequency of the measurements until the $R_p$ curves level off. It will be noted that for the experimental curves, such as in figure 4, there is not a definite high frequency plateau, but the reverse curvature is plain for some of them, and a close estimate of $G_\infty$ may be made by extrapolating the curve.

Figure 8 is an example of the curves obtained from making all the calculations of the previous section. By comparison with the curves of figure 7, it may be seen that the observed M value is small, and $\hat{\zeta}$ is high. This is the case for M, which is calculated to be 2.98 from the data. It is impossible to state the value for $\hat{\zeta}$ without curve fitting, which, as was remarked, is impractical. From the same data it is possible to make an estimate of the total number of charge carriers which for this case is $5 \times 10^{11}/cm^3$, a value certainly within reason.

$\tau_m$, the relaxation time, turns out to be $7 \times 10^{-8}$ seconds, again a reasonable value, as it may be seen that at frequencies corresponding to this, the curvature of the $R_p$ graphs tends toward the horizontal. A calculation of the mobility yields the rather low value $1.2 \times 10^{-9}$ $cm^2$/ volt second. Figures in the region of $10^{-4} cm^2$/volt second are often given for ions in electrolytic solutions, but here the material is semi-dry, which will certainly increase the viscosity. A further reason for the small value may lie in the possibility that in the intracellular material in its fairly dry state it is impossible for the ions to travel directly in the direction of the field, but they are required to detour along the strands of the gel structure, so that the measurement gives an apparent mobility, and not the true mobility on a molecular scale.

Figure 9 is a graph obtained from material at 65°C. The general shape of these curves resembles those taken at lower temperature, but it was impossible to get a complete determination of $G_\infty$ due to the interfering effect of the very high dissipation

on the bridge accuracy. However, by making a decent estimate it can be computed that $c_o$ is now $1.7 \times 10^{12}/cm^3$, $\tau_m$ is $1.6 \times 10^{-8}$ seconds, and $\mu$ is $3.5 \times 10^{-9} cm^2$/volt seconds. In general this accords with theory, in that at higher temperature the material is less viscous, resulting in high mobility and lower relaxation time. The additional number of carriers seems questionable in the light of the small temperature interval.

In order to make these calculations according to the methods of Macdonald, and have a decent curve shape, it was necessary to make several assumptions as to L, the distance between the electrodes. First tried was the distance between the electrodes of the dielectric constant cell, which gave completely unreasonable figures. A second approach was made using the dimension of the corn seed itself. This too gives values which are not at all probable. However, by selecting a possible size of the cells themselves, 1 micron, the values become realistic. It must be emphasized that the values given here are in no sense to be assumed exact, but merely reasonable values obtained on the basis of reasonable assumptions. The order of magnitude of these values is fairly certain for the reason that the experimental curves cross at very close to the value $\eta/m = 1$ required by the theory. Also, when curves are drawn with a difference of merely 2 micromicrofarads in measured capacitance, for instance, they are completely unrecognizeable as resembling figure 7. This sensitivity of curve shape to the values used in calculation gives assurance that this work is useable as an indication of ionic conditions within the cells of the corn seeds.

A final investigation of the ionic conditions was performed by making the plots shown in figures 10 and 11. These were constructed from the previously measured constants. These curves illustrate a form of the previously mentioned Arrhenius function. In order to calculate the activation energy by the use of this function it is necessary to determine the slope of the straight line portion of the graph. Simple manipulation gives the expression for the straight line. For instance, at 200 cps,

$$R_p = 5 \times 10^3 e^{\frac{1.5 \times 10^3}{T}}$$

Now taking the exponent and rewriting $\frac{1.5 \times 10^3}{T} = \frac{E}{kT}$, gives a value of $2.1 \times 10^{-13}$ ergs, slightly less than .2 electron volts. It is apparent that the slopes of the straight lines are all parallel, so that the activation energy is essentially constant. With references to figure 10 it may be seen that as colder temperatures are approached the curves break over, and have been shown to be parallel to the horizontal axis on some measurements. The significant feature of these curves is that the temperature of curvature depends on the frequency at which the measurements are made. Figure 11 shows the curves made from data on dehydrated seeds. At 100 cps it is seen that the activation energy is close to that of the normal seeds, but as the frequency increases merely to 500 cycles, the curvature becomes pronounced, and at 5000 cps the plot is bending toward its horizontal position.

There is a rather simple physical explanation for the frequency dependence of the temperature at which curvature begins. The cooling has merely increased the viscosity of the cellular material, so that

at higher frequencies the ionic conduction is out of phase with the field, and as soon as it is completely out of phase with the field, the graph will show no change on this scale with changes in temperature. Even with higher viscosity, at low frequencies the ions may stay in phase with the field, so that it is necessary to cool still more to get the levelling off effect. In the case of the dehydrated seeds it is thus apparent that the lack of moisture has increased the viscosity of the material and only moderate cooling is necessary to affect the ionic conductivity even at low frequencies.

## IV. Summary and Conclusions

Study of the tables of germination percentages for the various forms of treatments reveals that there is seldom more than one-half percent difference in germination percentage between the control seeds and the test samples. In one case, shown in table VI, there is a 1.1% difference, but a statistical examination shows that for this many samples, the difference is non-significant. It should be concluded from this that there was no effect demonstrated which may be specific for a given frequency.

Application of fields of 60,000 volts/cm produced heated effects which raised the temperature about 20°C, but under the conditions used for the other experimental work, temperature rises of only 1 to 2°C were noted. This temperature rise, combined with the possible statistical indication of an overall trend toward lower germination percentages for the entire group of test samples was the only effect demonstrated by the irradiation experiments.

The search for molecular absorption in seeds showed only two frequencies at which a reliable indication was found. Figure 6 shows the effects of absorption due to the presence of moisture in the seeds. The frequency of this absorption maximum corresponds to a frequency expected when the temperature dependent absorption of ice is extrapolated to room temperature. It is concluded that a certain amount of the moisture in the seeds is in a highly oriented form similar to that found in ice. By the same reasoning the absorption shown in figure 3 at -180°C is apparently due to a molecule whose room temperature absorption occurs at a much higher frequency than used in this work.

Measurement of the changes in parallel resistance at various frequencies as a function of temperature yield curves of the type shown in figure 10. These are typical of ionic conduction, and calculation gives a value of .2 electron volts as the activation energy under these conditions. It may be concluded, therefore, that the rises in low frequency dielectric constant and dissipation factor are due to ions moving in a viscous medium, and not to some specific property of large molecules in the cells.

Calculations based on data regarding the DC capacitance, parallel conductance, and space charge capacitance show that at room temperature there are about $5 \times 10^{11}$ charge carriers per cubic centimeter, moving with an apparent mobility of $1.2 \times 10^{-9}$ $cm^2$/volt second. It should be concluded that these figures, although not exact, are correct to order of magnitude, due to the agreement of the experimental curves of figure 8, with the theoretical curves of figure 7.

Table I

Comparison of germination percentages for 2 hour exposures at 1200 volts/cm.

| 500 cps | Control % | Test % |
|---|---|---|
| | 100 | 100 |
| | 100 | 98 |
| | 96 | 96 |
| | 98 | 96 |
| Average | 98 | 98 |
| % germination | 98.4% | 97.6% |

| 1000 cps | Control % | Test % |
|---|---|---|
| | 100 | 100 |
| | 100 | 100 |
| | 100 | 98 |
| | 98 | 96 |
| Average | 98 | 100 |
| % germination | 99.2% | 98.8% |

| 2500 cps | Control % | Test % |
|---|---|---|
| | 100 | 100 |
| | 98 | 100 |
| | 98 | 96 |
| | 98 | 98 |
| Average | 96 | 96 |
| % germination | 98 % | 98% |

| 5000 cps | Control % | Test % |
|---|---|---|
| | 100 | 100 |
| | 98 | 96 |
| | 98 | 98 |
| | 96 | 100 |
| Average | 98 | 98 |
| % germination | 98% | 98.4% |

| 100 kc | Control % | Test % |
|---|---|---|
| | 100 | 98 |
| | 100 | 98 |
| | 100 | 100 |
| | 98 | 100 |
| Average | 98 | 98 |
| % germination | 99.2% | 98.8 |

Table II

Comparison of germination percentages for 7 hour exposures at 1200 volts/cm.

| | Control % | Test % |
|---|---|---|
| 500 cps | 98 | 100 |
| | 98 | 96 |
| | 96 | 98 |
| | 100 | 98 |
| | 100 | 98 |
| Average % germination | 98.4 % | 98% |
| 2500 cps | 100 | 96 |
| | 98 | 100 |
| | 98 | 100 |
| | 100 | 98 |
| | 98 | 100 |
| Average % germination | 98.8% | 98.8 |
| 5000 cps | 100 | 100 |
| | 98 | 100 |
| | 98 | 98 |
| | 98 | 98 |
| | 100 | 100 |
| Average % germination | 98.8% | 98.8% |

Table III

Comparison of germination percentages for 7 hour exposures at 12,000 volts/cm.

| 125 kc | Control % | Test % | 145 kc | Control % | Test % |
|---|---|---|---|---|---|
| | 100 | 98 | | 100 | 94 |
| | 100 | 96 | | 98 | 96 |
| | 94 | 98 | | 98 | 100 |
| | 98 | 98 | | 96 | 98 |
| Average | 98 | 100 | Average | 96 | 98 |
| % germination | 98% | 98% | % germination | 97.6% | 97.2% |

| 220 kc | Control % | Test % |
|---|---|---|
| | 96 | 98 |
| | 96 | 96 |
| | 96 | 96 |
| | 94 | 94 |
| Average | 96 | 96 |
| % germination | 95.6% | 95.6% |

Table IV

Comparison of germination percentages for 6 hour exposure; at 20,000 volts/cm, spark coil source.

| | Control % | Test % |
|---|---|---|
| | 100 | 98 |
| | 100 | 98 |
| | 98 | 98 |
| | 98 | 100 |
| | 96 | 98 |
| | 96 | 94 |
| | 100 | 100 |
| | 100 | 100 |
| Average % germination | 98.5% | 98.2% |

Table V

Comparison of germination percentages for 5 hour exposures at 12,000 volts/cm, 48°C.

| 125 kc | Control % | Test % |
|---|---|---|
| | 100 | 100 |
| | 100 | 100 |
| | 98 | 98 |
| | 96 | 94 |
| Average | 96 | 96 |
| % germination | 98% | 97.6% |

Table VI

Comparison of germination percentages for 5 hour exposures at 1200 volts/cm, 48°C.

| 500 cps. | Control % | Test % |
|---|---|---|
| | 96 | 92 |
| | 100 | 98 |
| | 100 | 94 |
| | 96 | 94 |
| | 96 | 100 |
| | 100 | 100 |
| | 100 | 98 |
| | 98 | 96 |
| | 100 | 98 |
| | 98 | 94 |
| | 100 | 94 |
| | 94 | 98 |
| | 96 | 98 |
| | 94 | 98 |
| | 98 | 98 |
| Average % germination | 97.7% | 96.6% |

Table VII

Comparison of germination percentages for 2 hour exposures at 1200 volts/cm.

| 5000 cps | Control % | Test % |
|---|---|---|
| | 100 | 100 |
| | 98 | 98 |
| | 98 | 94 |
| | 96 | 98 |
| | 96 | 94 |
| | 98 | 100 |
| | 96 | 88 |
| | 96 | 100 |
| | 100 | 96 |
| | 96 | 98 |
| | 100 | 100 |
| | 98 | 100 |
| | 100 | 100 |
| | 98 | 98 |
| | 96 | 96 |
| | 94 | 98 |
| Average % germination | 97.5% | 97.4 % |

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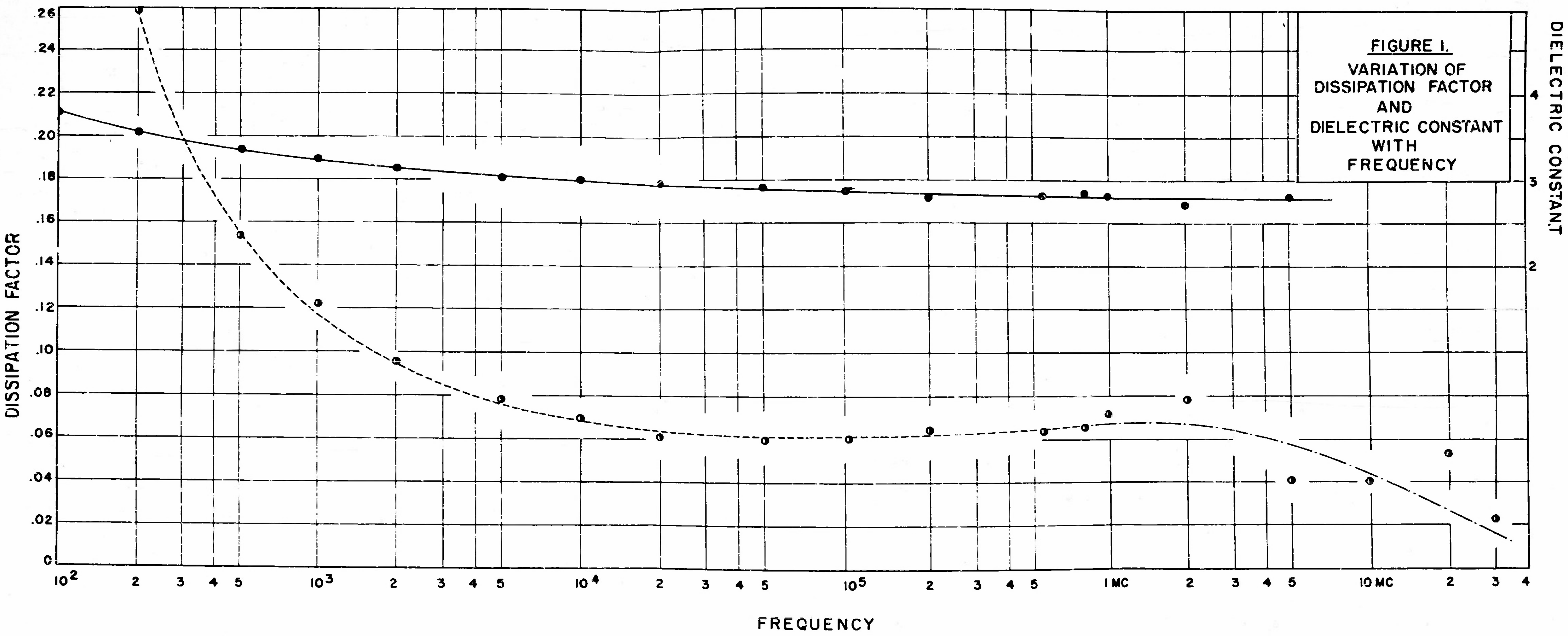


FIGURE I.
VARIATION OF
DISSIPATION FACTOR
AND
DIELECTRIC CONSTANT
WITH
FREQUENCY
DISSIPATION FACTOR
DIELECTRIC CONSTANT
FREQUENCY
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
4
3
2
10^2 2 3 4 5 10^3 2 3 4 5 10^4 2 3 4 5 10^5 2 3 4 5 1 MC 2 3 4 5 10 MC 2 3 4

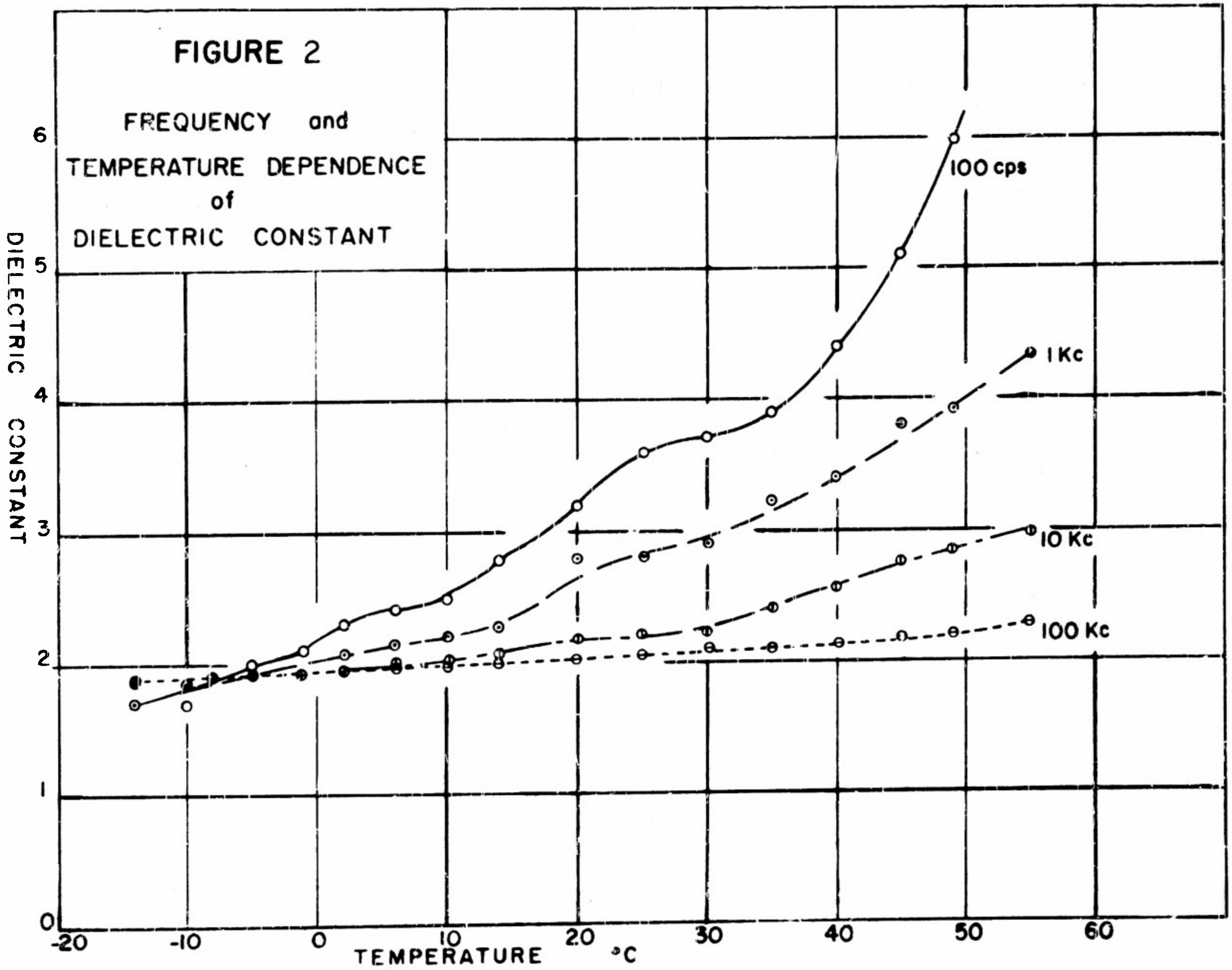



FIGURE 2

FREQUENCY and TEMPERATURE DEPENDENCE of DIELECTRIC CONSTANT

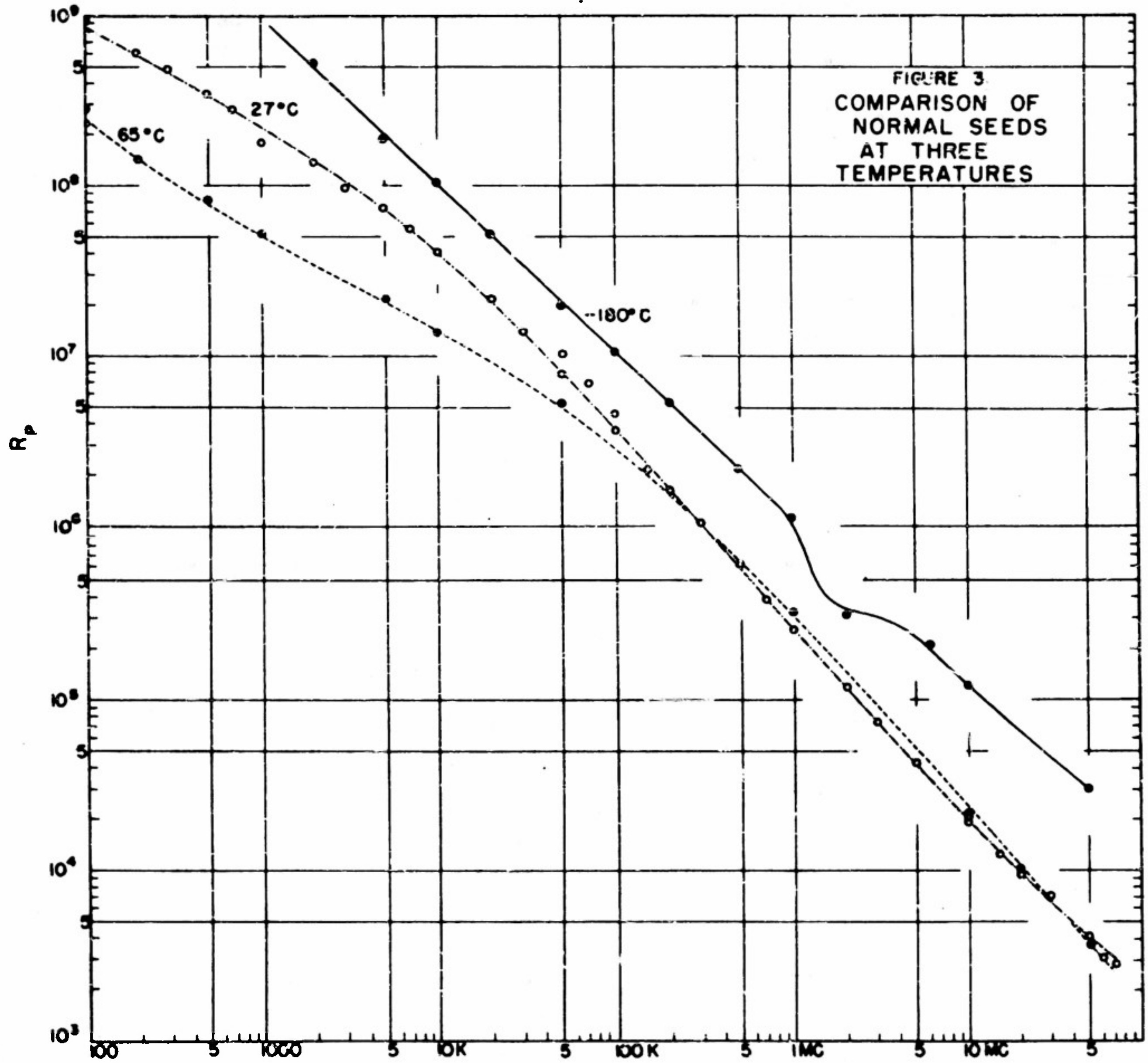


FIGURE 3
COMPARISON OF
NORMAL SEEDS
AT THREE
TEMPERATURES
27°C
65°C
-180°C
$R_p$
$10^9$
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
100
1000
10K
100K
1MC
10MC

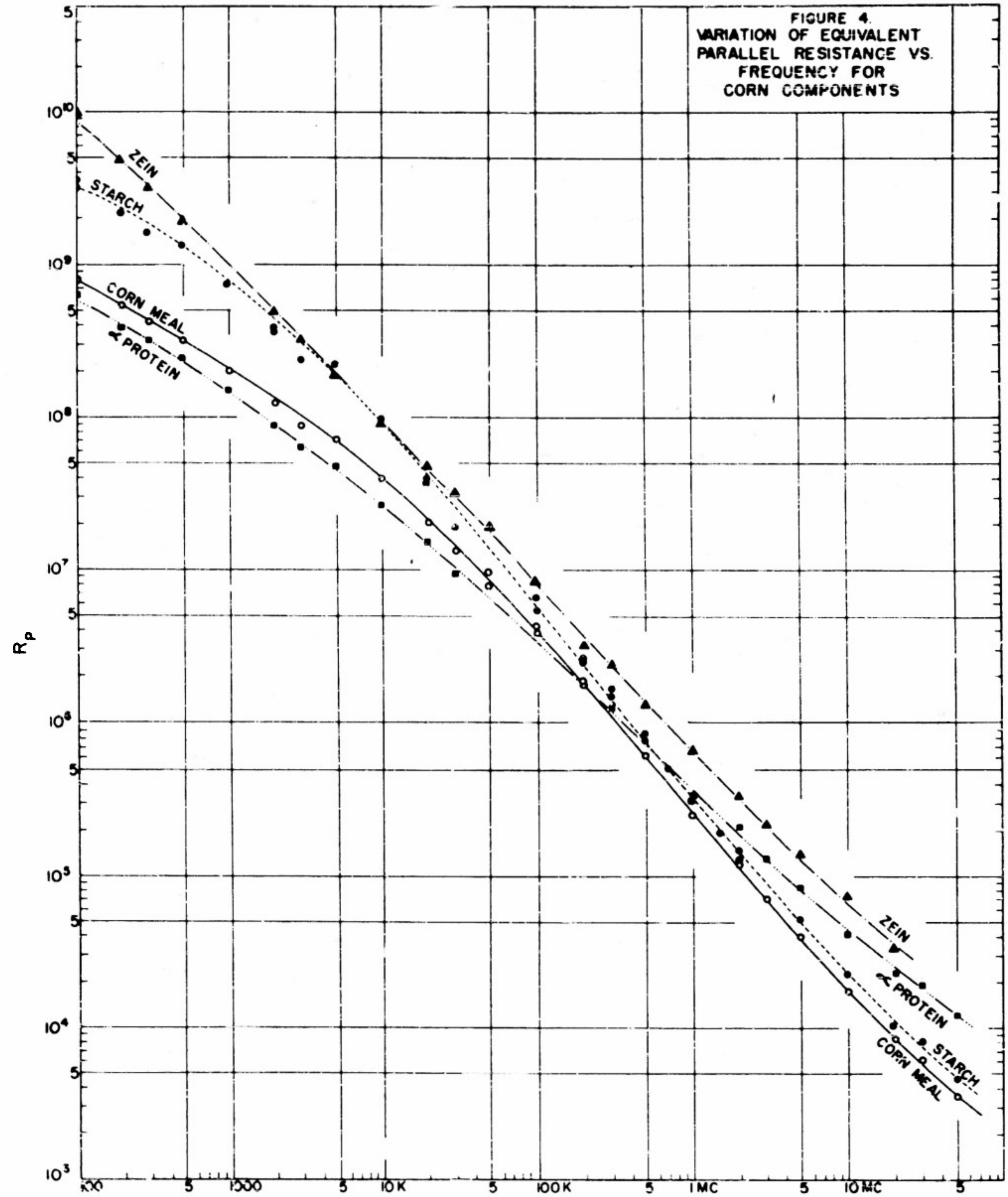


FIGURE 4.
VARIATION OF EQUIVALENT
PARALLEL RESISTANCE VS.
FREQUENCY FOR
CORN COMPONENTS
ZEIN
STARCH
CORN MEAL
α PROTEIN
R_P
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
100
1000
10 K
100 K
1 MC
10 MC

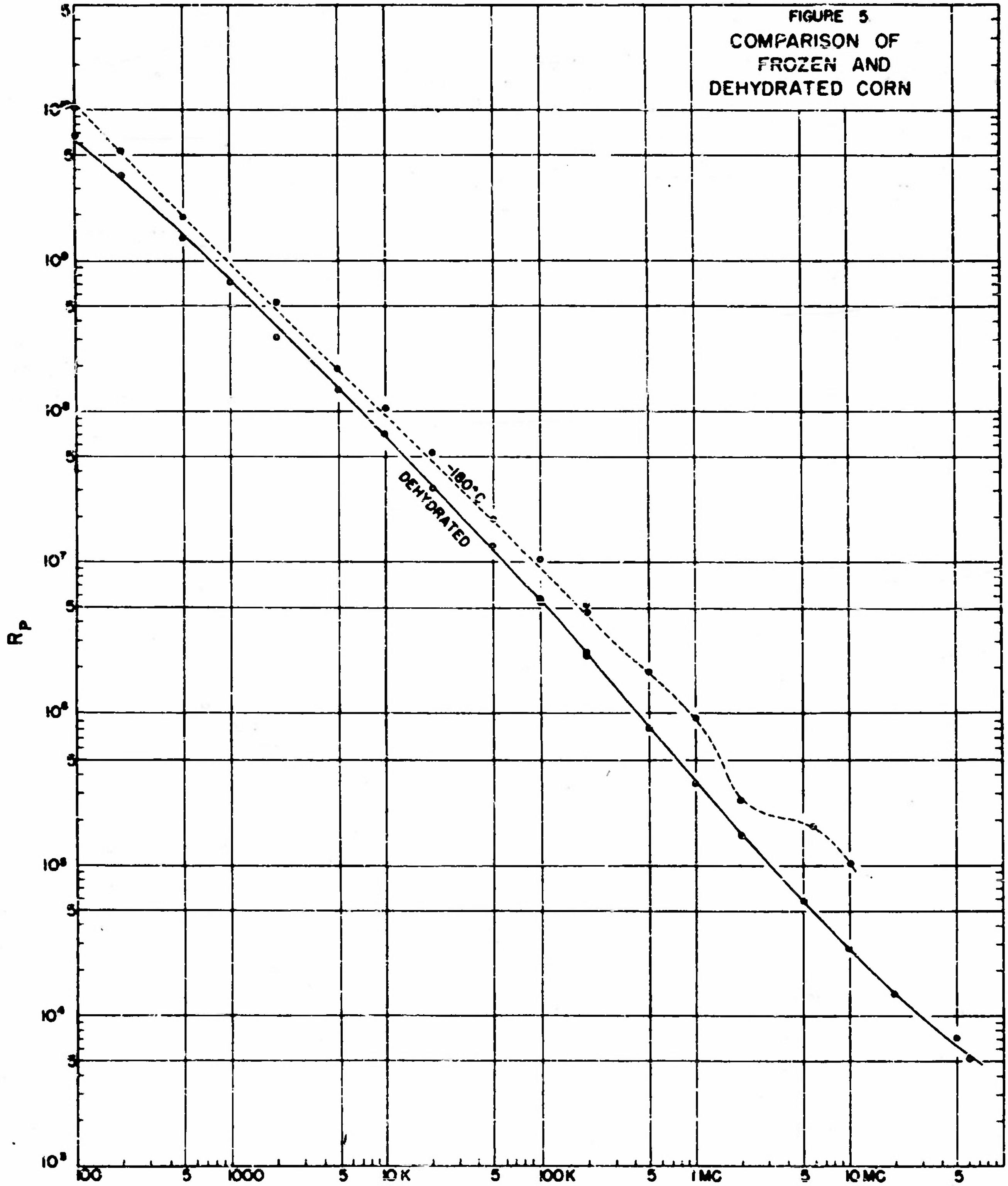


FIGURE 5
COMPARISON OF
FROZEN AND
DEHYDRATED CORN
-180°C
DEHYDRATED
$R_p$
$10^{10}$
5
$10^9$
5
$10^8$
5
$10^7$
5
$10^6$
5
$10^5$
5
$10^4$
5
$10^3$
100
5
1000
5
10 K
5
100K
5
1 MC
5
10 MC
5

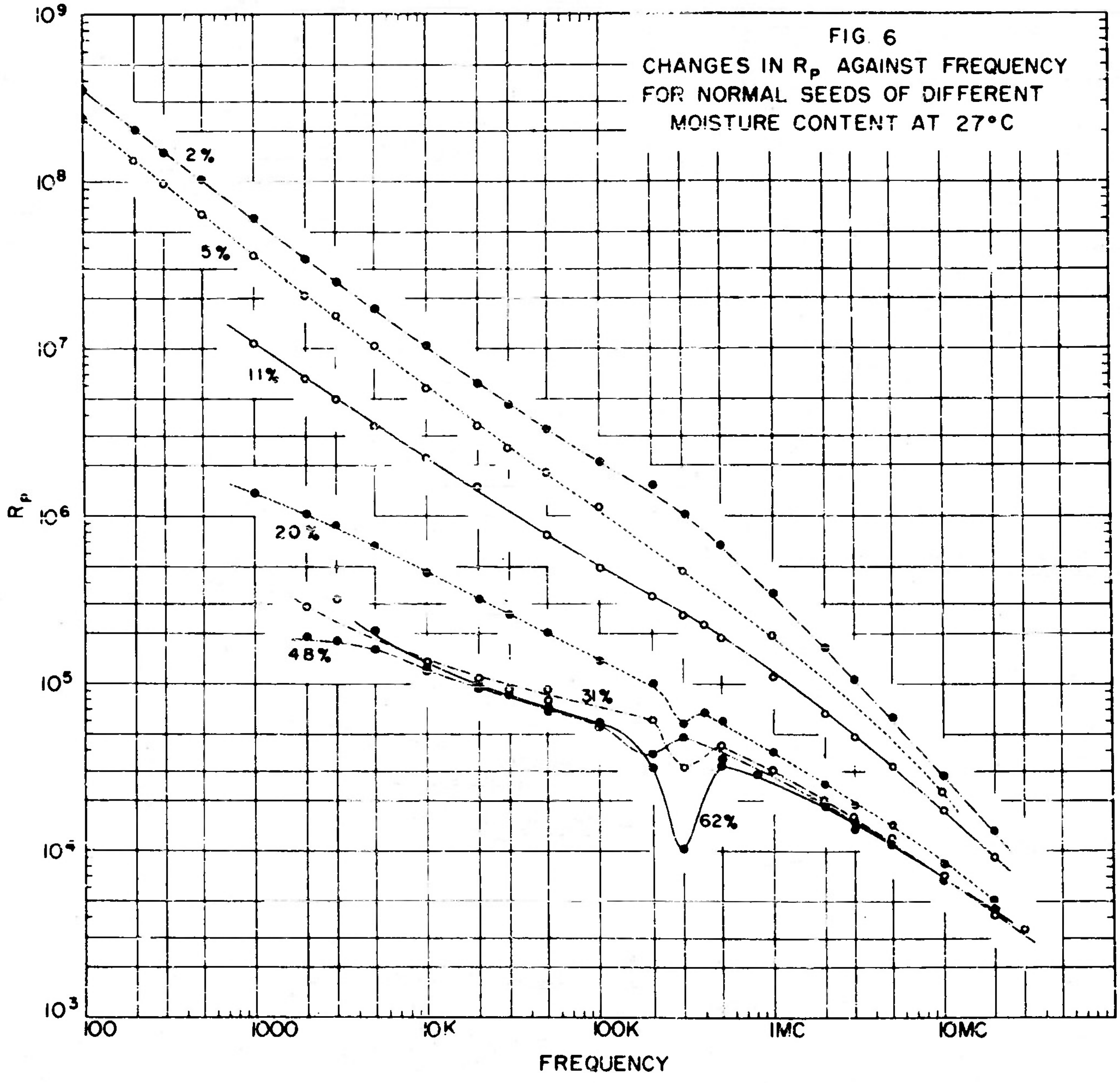
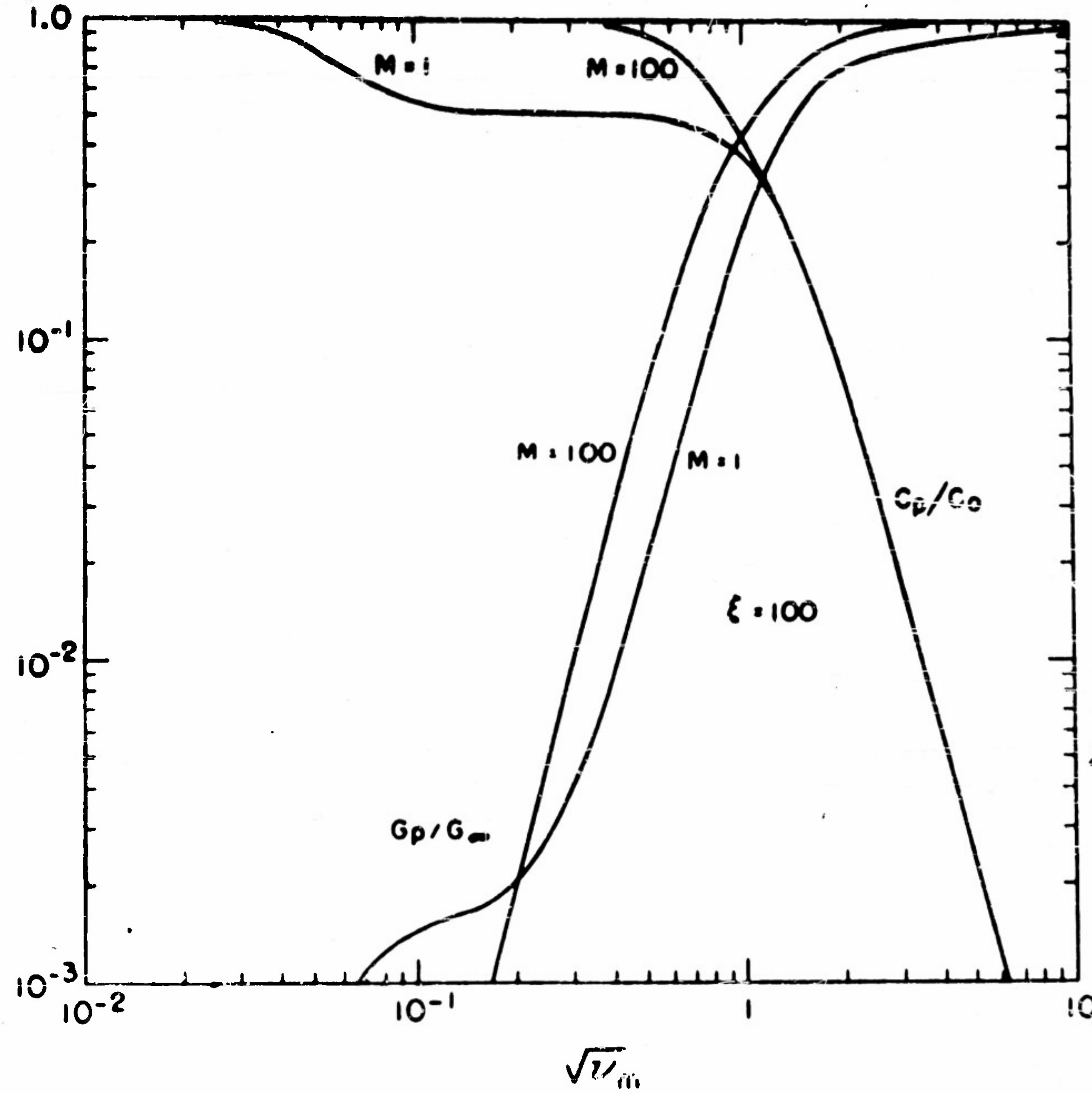


FIG. 6
CHANGES IN $R_p$ AGAINST FREQUENCY
FOR NORMAL SEEDS OF DIFFERENT
MOISTURE CONTENT AT 27°C
$10^9$
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
$R_p$
2%
5%
11%
20%
31%
48%
62%
100
1000
10K
100K
1MC
10MC
FREQUENCY




Doubly logarithmic plot of $C_P/C_0$ and $G_P/G_\infty$ *versus* $\sqrt{\nu_m}$ for $\xi = 100$ and $M = 1$ and 100.

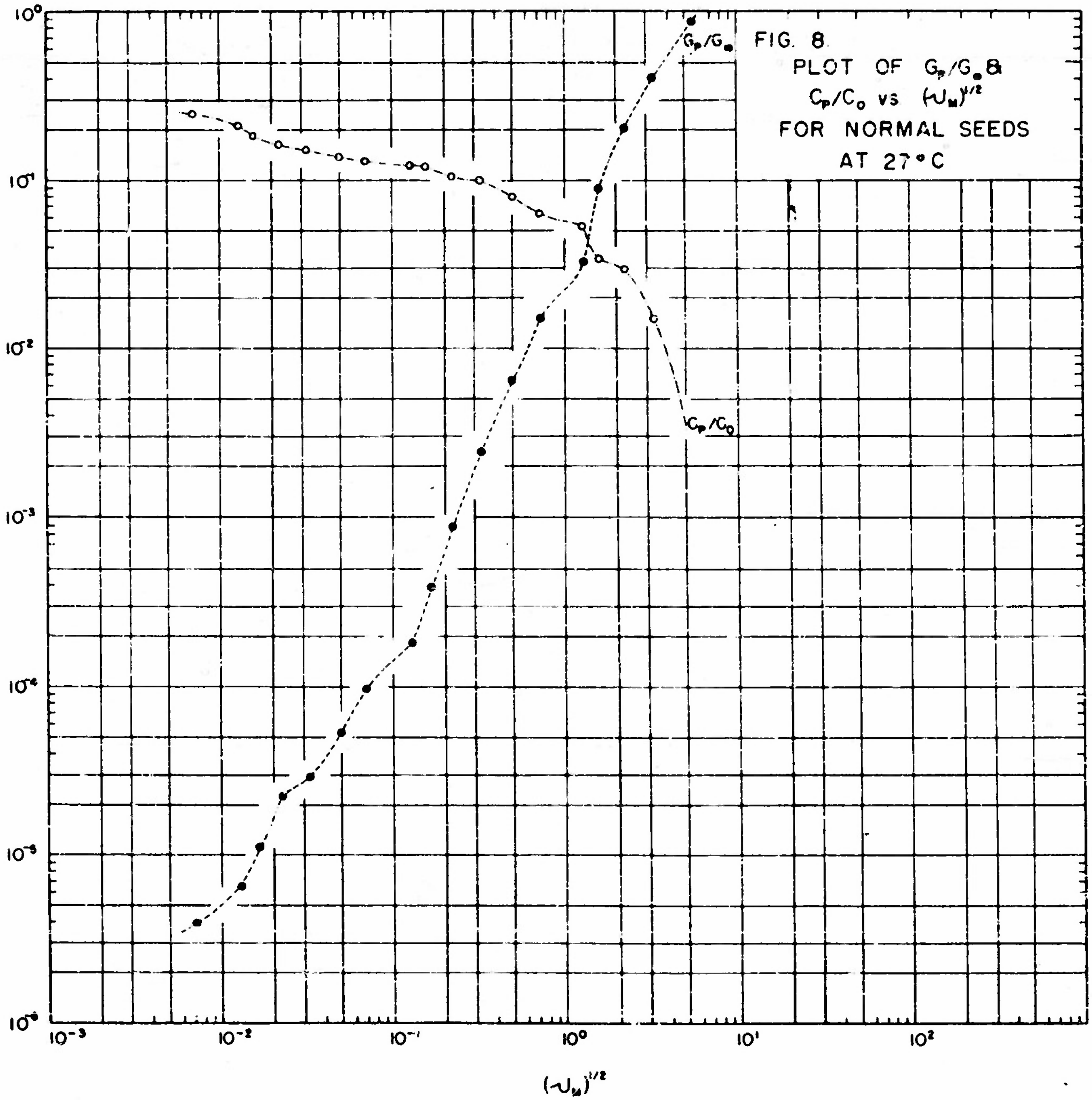



FIG. 8
PLOT OF $G_p/G_\infty$ & $C_p/C_0$ vs $(-\upsilon_M)^{1/2}$
FOR NORMAL SEEDS
AT 27 °C

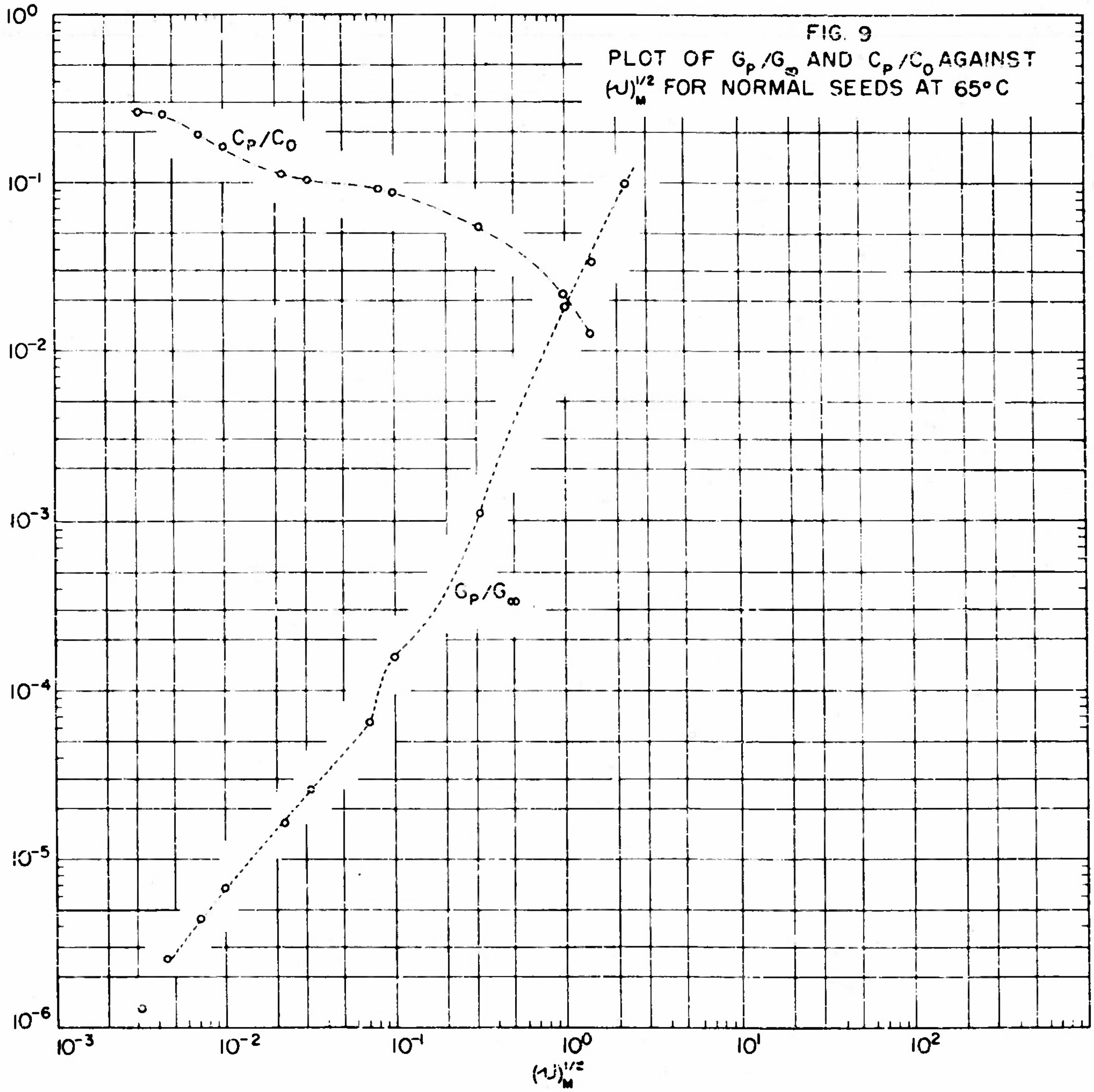


FIG. 9
PLOT OF $G_p/G_\infty$ AND $C_p/C_0$ AGAINST $(-U)_M^{1/2}$ FOR NORMAL SEEDS AT 65°C
$C_p/C_0$
$G_p/G_\infty$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
$(-U)_M^{1/2}$

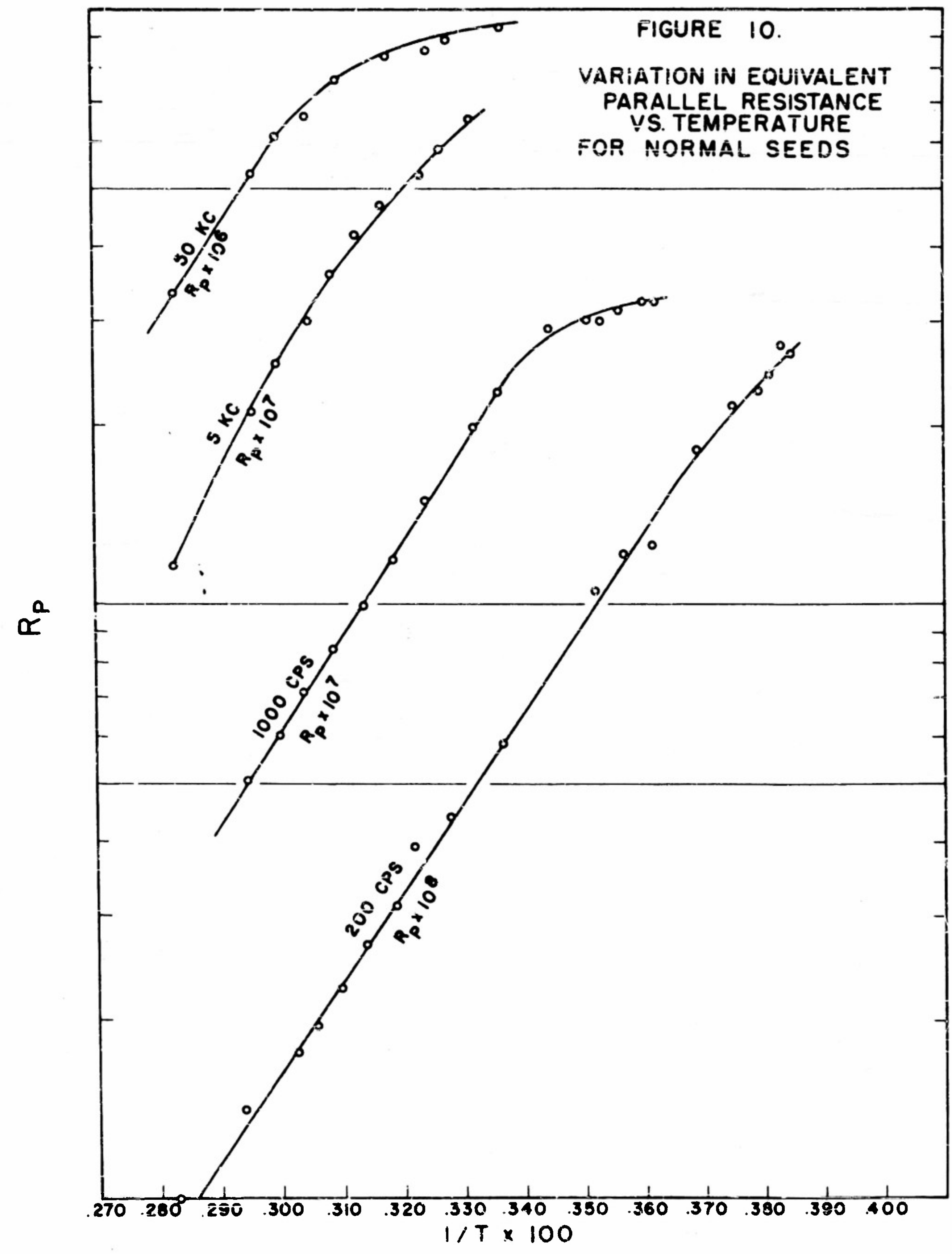


FIGURE 10.
VARIATION IN EQUIVALENT
PARALLEL RESISTANCE
VS. TEMPERATURE
FOR NORMAL SEEDS
50 KC
$R_p \times 10^6$
5 KC
$R_p \times 10^7$
1000 CPS
$R_p \times 10^7$
200 CPS
$R_p \times 10^8$
$R_P$
.270 .280 .290 .300 .310 .320 .330 .340 .350 .360 .370 .380 .390 .400
1/T x 100

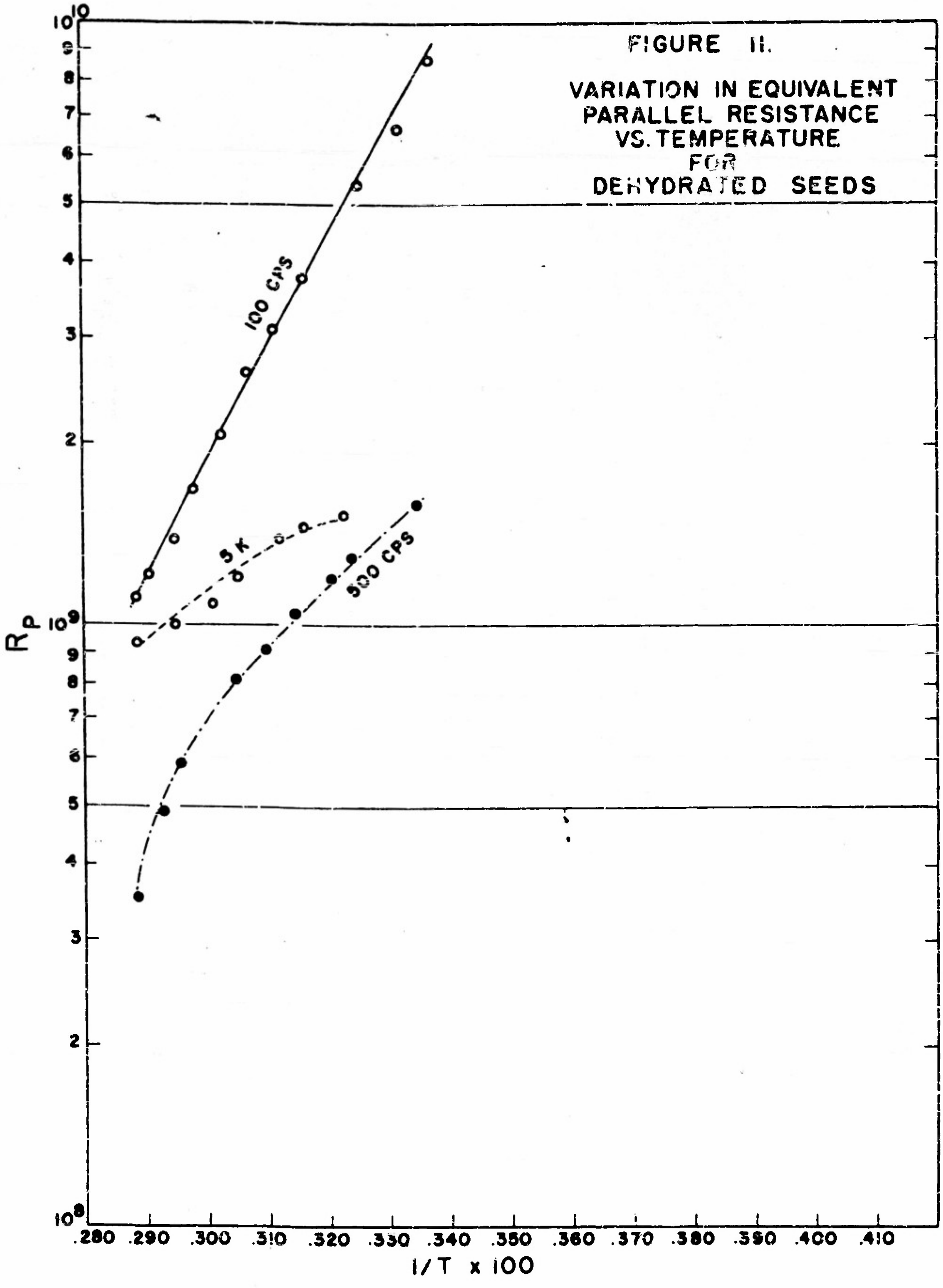
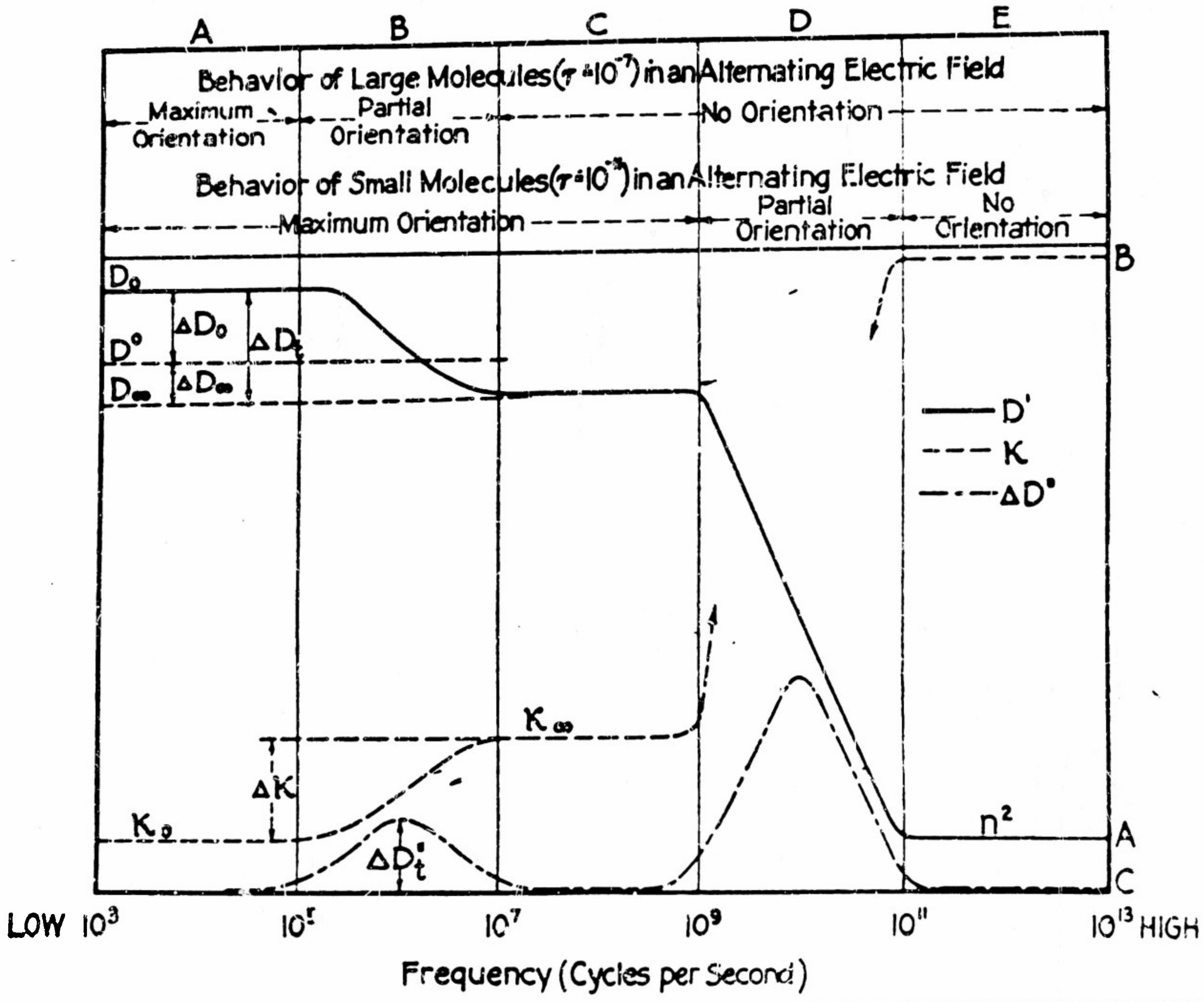


FIGURE II.
VARIATION IN EQUIVALENT PARALLEL RESISTANCE VS. TEMPERATURE FOR DEHYDRATED SEEDS
100 CPS
5 K
500 CPS
$R_P$
$10^{10}$
$10^9$
$10^8$
.280 .290 .300 .310 .320 .330 .340 .350 .360 .370 .380 .390 .400 .410
1/T x 100


A
B
C
D
E
Behavior of Large Molecules($\tau \approx 10^{-7}$) in an Alternating Electric Field
Maximum Orientation
Partial Orientation
No Orientation
Behavior of Small Molecules($\tau \approx 10^{-9}$) in an Alternating Electric Field
Maximum Orientation
Partial Orientation
No Orientation
$D_0$
$D^0$
$D_\infty$
$\Delta D_0$
$\Delta D_t$
$\Delta D_\infty$
$D'$
$K$
$\Delta D''$
$K_\infty$
$\Delta K$
$K_0$
$\Delta D_t''$
$n^2$
B
A
C
LOW $10^3$
$10^5$
$10^7$
$10^9$
$10^{11}$
$10^{13}$ HIGH
Frequency (Cycles per Second)